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THE ANALCITE BASALTS OF SARDINIA

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Introduction.—In his well-known paper[1] entitled "Die Producte des Vulcans Monte Ferru," Doelter first noted the presence of "leucite basalts" at this volcano, as well as near Pozzo Maggiore, giving a brief description and an analysis. Later, Dannenberg[2] and Deprat[3] confirmed the occurrence of leucite rocks at Ferru, and showed that these flows belong to the closing period of volcanic activity. In the autumn of 1905 I visited Sardinia for the Carnegie Institution of Washington, making a special study of the different volcanoes of this island. Although my observations were necessarily brief, I was able to confirm the opinion of these geologists. The first analysis, which I made some years ago, of a specimen from Scano gave such unexpected results as regards the alkalies that I made two others of these so-called leucite rocks from other localities. All three were in harmony. Since these rocks have always been considered to be and have been cited as being leucitic, although in reality the so-called leucite is analcite, it seemed to me that a special note would be of interest. The lavas of Monte Ferru and of the other Sardinian volcanoes will be described in other papers.

I have to thank my friends, Professor J. V. Lewis for the photographs of the thin sections, and Doctors F. E. Wright and H. E. Merwin of the Geophysical Laboratory for the optical study of the analcite and biotite.

Occurrence.—Although these basalts vary somewhat in their modal characters, yet they are so closely allied that they may well be described together. One prominent locality, already noted by Doelter,[4] is a massive flow, from 6 to 10 m. thick, on the other side of a small stream just north of Scano, a village on the northeastern flank of Monte Ferru. The basalt here overlies a flow of the ordinary gray trachyte of the Sennariolo type, the trachyte resting on white tuffs. Below these are tertiary marls. To the south of Scano is another flow, possibly connected with that to the north. This forms a ridge known as Binzale Prunu, which extends in a southeast direction for about 2 km. and shows three summits, called Monti Columbargiu, Martu, and Lepere. I collected lavas from the Scano flow, and from that of Binzale Prunu along the road between Scano and Cuglieri below Monte Columbargiu, and at a quarry below Monte Martu called Cava Tuvamurtas. Similar basalts were also collected at a small cone west of Bonorva, a small town east of Pozzo Maggiore, which apparently belongs to the closing phase of the last period of small cones in Sardinia. At a locality called Ghizo, to the west of Monte Urtigu, the culminating point of Monte Ferru, there is a small exposure of a similar rock containing many copper-colored biotite tables. The color of these biotite crystals makes the peasants believe that the rock is an ore of copper, and a peasant whom I met near by told me about a King Mastino, a sort of *Bergkönig*, to whom all the copper belongs. It is supposed that this king lives beneath the earth and has cast a spell upon the copper ore so that men cannot extract the copper from it.

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[1] C. Doelter, *Denks. Akad. Wiss. Wien*, XXXIX (1878), 41.

[2] A. Dannenberg, *Neu. Jahrb.*, Beil. Bd., XXI (1905), 48.

[3] G. Deprat, *C.R.*, CLV (1907), 823.

[4] C. Doelter, *op. cit.*, p. 78.

Megascopic characters.—These lavas are all very dense, compact, and aphanitic. Apart from nodules of olivine and augite, to be described presently, the Scano flow shows few phenocrysts, a few small crystals of augite and olivine and very sparing biotites being the only ones visible. This lava is a rather darkish gray. The lava of Bonorva, which also carries olivine nodules, much resembles this except that there is no biotite. The lava flow of Binzale Prunu is almost black, quite aphanitic, though with alteration it assumes a brownish or even reddish color. In this are many tables of a bronzy biotite which are smaller but more numerous in the lava from the quarry, but larger and less numerous in that from Monte Columbargiu. The tables of this biotite are all a light chestnut brown, but when altered have a red color and a luster resembling that of copper. Dr. Merwin found that the angle

$2E = 40°-45°$ and the refractive index $\gamma_{na} = 1.65-1.655$. These figures are high and much resemble those of some biotites of Vesuvius. There was not sufficient material to make an analysis of them. In this rock also there occurred rather abundant crystals (1–3 mm.) of a pale, greenish olivine. The rock of Ghizo is a dark brick red with many bronzy biotite tables. I was not able to obtain any fresh specimens of this, so that for the present it may be left out of consideration.

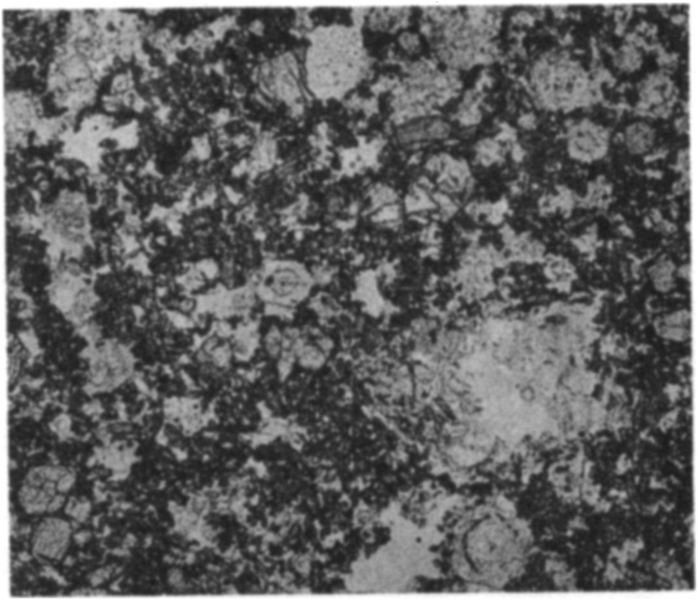

FIG. 1.—Analcite basalt, Scano

Microscopic characters (*Figs. 1 and 2*).—In all these basalts, the phenocrysts of augite and olivine are not very prominent in the thin section. The olivines vary from 0.1 to 0.5 mm. in diameter, and are generally anhedral, euhedral crystals being comparatively rare. They are colorless and quite fresh, except for a thin border of transparent bright-yellow alteration product, apparently allied to iddingsite, the amount of which is never very great. There is never any serpentinization. The augites are colorless, anhedral, smaller than the olivines, and comparatively rare. One sees scattered through the groundmass circular areas which are clear and colorless. The diameter of these varies somewhat, in those of Scano being from 1 to 2 mm., while in that from Binzale Prunu it is never over 0.1 mm. These are almost exactly the same as the small leucites of the leucitic lavas of the Italian Peninsula. The boundaries are more or less well defined, often by a circular line of small grains. They contain the ordinary inclusions common to leucite, of augite and magnetite microlites, which form either a central core or a circular wreath. They are never radially arranged. All these leucite-like crystals are absolutely isotropic, even when the sensitive tint is used, and no optical anomalies or twinning phenomena are seen between crossed nicols. The observations of Dr. Wright showed that these crystals have a refractive index of 1.502, which is lower than that of leucite and above that of analcite.

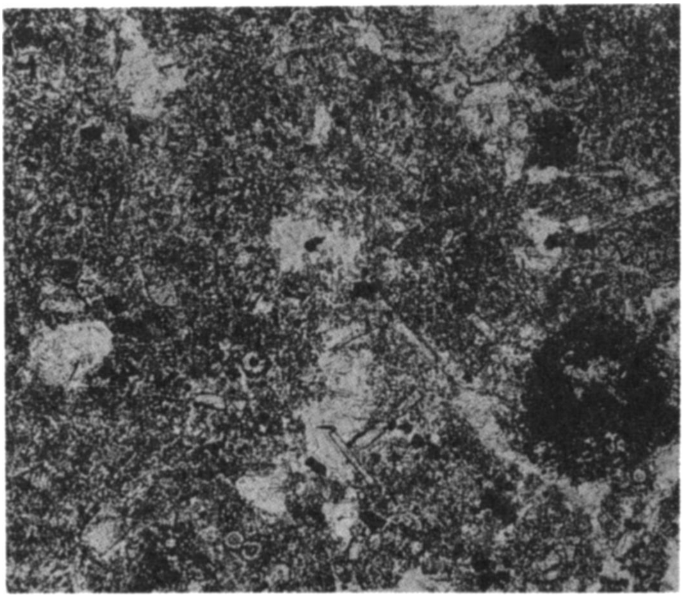

FIG. 2.—Analcite basalt, Monte Columbargiu

The microscopic groundmass is composed of abundant, very small prisms of augite and fewer anhedral grains of olivine and magnetite, scattered without any definite arrangement in an abundant colorless glass. Nothing was found which could be considered to be feldspar. There are some small needles of apatite.

Nodules.—The lava flow north of Scano is remarkable for the abundance of nodules of olivine and augite, which have been already partially described by Doelter.[1] Those of olivine seem to be most numerous. They are rounded, varying in size from that of a hazelnut to that of one's fist. They are composed of grains, from 1 to 2 mm. in diameter, of a transparent olivine, of a light greenish-yellow color, with a few small grains of magnetite. These grains are not very coherent, the nodules crushing down readily beneath the finger. An analysis of this olivine, extremely fresh, carefully purified and dried at 110°, gave me the results in A (Table I), those in B being an analysis by Doelter (*op. cit.*, p. 78). The specific gravity was 3.307 at 20°. The amount of nickel is noteworthy, as is also the entire absence of chromium, an element often occurring in olivine. There was only an unweighable trace of manganese and absolutely no lime. Leaving out of consideration the very small amounts of alumina and ferric oxide, as impurities, the ratio RO:(Si, Ti)O_2 = 1.99; 1.00, which is that of an orthosilicate. That of FeO:MgO = 1:10.5, so that the olivine is distinctly magnesian. The optical properties of this olivine will be studied later.

TABLE I

	A			B
SiO_2	41.24	0.687	0.689 (1.00)	43.77
TiO_2	0.10	0.001		...
Al_2O_3	0.21	0.002		...
Fe_2O_3	0.48	0.003		0.61
Cr_2O_3	Nil			...
FeO	8.36	0.116	1.367 (1.99)	24.90
MnO	Trace			...
NiO	0.21	0.003		...
MgO	49.90	1.248		29.21
CaO	Nil			Trace
	100.62			98.49

Doelter's analysis is clearly defective. The sum is very low and the relation RO:SiO_2 does not approach that of an orthosilicate.

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[1] C. Doelter, *op. cit.*, p. 78.

Elsewhere[1] Doelter speaks of an olivine of Scano, of which Ippen made an analysis (not given). It is stated that the results of this correspond to the composition $7(Mg_2SiO_4) \cdot 3(Ca_2SiO_4)$. This would be a most extraordinary olivine, unique in mineralogy, and almost corresponding to a monticellite, although occurring in an igneous rock. But unfortunately the analysis has never been published, and one does not even find it in the elaborate *Handbuch der Mineralchemie* of Doelter, either under monticellite or under olivine. Regarding this olivine, Professor Doelter has been kind enough to write me (December 31, 1907) that it is white, forming isolated grains, and not in granular nodules like the olivine described above. He says that its locality is near Scano, that it is very rare, and that it has nothing in common with the olivine of the nodules.

The nodules of augite are subangular and smaller than the others, from 1 to 5 cm. in diameter. They are very compact, not granular, each one made up of a single crystal of the pyroxene, often twinned, and more or less split up through cleavage. The pyroxine is greenish-black, and it seems to be free from inclusions. An analysis gave me the following results:

SiO_2	50.13	NiO	0.02
TiO_2	1.91	MgO	13.73
Al_2O_3	7.08	CaO	20.06
Fe_2O_3	1.10	Na_2O	1.88
FeO	4.41	K_2O	0.25
MnO	0.05	H_2O	0.11
			100.73

Its chemical composition will be discussed later, when its optical properties shall have been studied.

Chemical composition.—Analyses made by me of three of these basalts are here given (Table II), along with several others of related rocks.

The three analyses of Sardinian basalts resemble each other quite closely in their general features. As regards most of the constituents, they are not specially noteworthy. Silica is rather low for basalts, and titanium is high, the latter a feature common to the rocks of Sardinia, as has been already pointed out.[1] The presence of a noteworthy amount of nickel is also of interest. The most striking feature—when the presence of "leucite" is considered—is the small amount of alkalies and the dominance of soda over potash. The presence in all three of from 2½ to 4 per cent of water, in spite of the evident freshness of the rocks, is also noteworthy.

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[1] C. Doelter, *Phy. Chem. Miner.* (1905), 64.

TABLE II

	A	B	C	D	E	F	G
SiO_2	44.85	44.37	46.54	45.59	44.16	40.81	42.30
Al_2O_3	12.55	11.36	12.68	12.98	12.96	13.08	18.22
Fe_2O_3	3.33	7.23	3.41	4.97	8.07	6.40	17.30
FeO	5.30	3.49	5.29	4.70	3.10	7.20	....
MgO	10.27	9.28	10.09	8.36	10.83	10.03	6.66
CaO	8.32	8.50	8.00	11.09	12.26	10.12	11.01
Na_2O	4.77	3.67	5.11	4.53	1.32	2.43	1.31
K_2O	0.72	0.74	1.64	1.04	0.72	0.31	2.93
H_2O+	2.01	3.28	2.35	3.40	2.41	3.97	0.55
H_2O-	0.95	1.95	0.25	0.51	0.46	0.82	....
TiO_2	5.07	5.21	3.98	1.32	2.06	3.86	....
ZrO_2	....	....	....	0.03	....	....	....
P_2O_5	1.17	0.99	0.91	0.91	1.03	0.88	Trace
Cl	....	....	....	0.05	....	....	....
MnO	0.07	....	....	0.14	....	0.07	Trace
NiO	0.23	....	....	....	....	....	....
BaO	....	....	....	0.13	....	....	....
SrO	....	....	....	0.12	....	....	....
	99.60	100.07	100.25	99.87	99.98	99.98	100.28

A. Analcite basalt [III. (5) 6. 2. 5]. Scano, Monte Ferru, Sardinia. H. S. Washington, analyst.

B. Analcite basalt [III. 5. (2) 3. (4) 5]. Monte Columbargiu, Monte Ferru. H. S. Washington, analyst.

C. Analcite basalt [III. 6. 1 (2). 4]. Bonorva, Sardinia. H. S. Washington, analyst.

D. Analcite basalt [III. 6. 2″ 4 (5)]. The Basin, Cripple Creek, Colorado. Hillebrand, analyst. Cross, *Jour. Geol.*, V (1897), 689.

E. Leucite basalt [III. 5. 4. 4]. Dobernberg, near Tetschen, Bohemia. R. Pfohl, analyst. J. E. Hibsch, *T.M.P.M.*, XV (1896), 255.

F. Analcite basalt [III. 5.″ 4.″ 5]. Rathjordan, County Limerick, Ireland. G. T. Prior, analyst. G. T. Prior, *Min. Mag.*, XV (1910), 317.

G. Leucite basalt. Scano, Monte Ferru, Sardinia. C. Doelter, analyst. C. Doelter, *Denks. Akad., Wiss. Wien*, XXXIX (1878), 80.

Doelter's analysis (G) of the Scano rock is obviously at fault in several particulars. The alumina is much too high because of the non-separation of TiO_2 and P_2O_5, and probably also in part through the incomplete separation of MgO from Al_2O_3, as his MgO is much lower than that of any of the three rocks analyzed by me. His Fe_2O_3 is also undoubtedly too high (apart from the non-determination of FeO), presumably because zinc was used for the reduction preparatory to titration with permanganate, part of the TiO_2 being thus reduced and estimated as Fe_2O_3. His alkalies are also low, and it seems possible that they have been interchanged. This analysis may therefore be left entirely out of consideration. Dannenberg (*op. cit.*, p. 50) gives the silica percentage of the Scano rock as 44.16, which agrees very well with my results, especially as a little silica would be recovered from the alumina precipitate.

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[1] H. S. Washington, *Q.J.G.S.*, LXIII (1907), 69.

Occurrence of analcite.—The results of these analyses render it highly improbable that the leucitic mineral is really leucite, and indicate clearly that it is analcite. To test this, the alkalies were determined in the portion of the Scano rock soluble in warm dilute hydrochloric acid. This gave $Na_2O=2.66$ and $K_2O=0.12$ in percentages of the rock; that is, more than half the soda and about one-sixth of the potash. Some of this soda is probably derived from the glass base, but its amount is so great, and that of potash so small, that it leaves no doubt that the rounded isotropic crystals are analcite. The entire absence of twinning lamellae and optical anomalies is also in harmony with this supposition, as it is well known that analcite, especially when not freely crystallized in cavities, is much less prone to show such phenomena than is leucite.[1]

The very fresh condition of the rocks analyzed precludes the idea that the analcite is secondary and replaces an original leucite—a supposition which is often invoked apparently only because of a disbelief that a hydrated, zeolitic mineral like analcite can be primary. The occurrence of primary analcite has been shown by several petrographers,[2] and there is also considerable experimental evidence, which cannot be gone into here, that confirms the view that such a primary character is not only quite possible, but very probable in many cases. Indeed, in view of the experimental formation of analcite at temperatures of 500° and higher, the known presence of water in rock magmas, and the great lowering of the melting-point through its presence, the primary character of the analcite is the only rational view in such cases as these and many others, where the rock is unquestionably fresh and unaltered. Such an explanation is far simpler and more intelligible than the invocation of the entire, or almost entire, replacement of potash by soda in a single mineral of the rock through assumed soda-bearing solutions of quite hypothetical origin, with no alteration of the other minerals. At the same time, of course, there is no question that in some cases, where the rock has undergone alteration, the analcite present is secondary, as it is in that from Rathjordan.

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[1] The absence of cleavage does not militate against the idea here advanced, as it is not a strongly marked characteristic of small analcites in thin section.

[2] W. Lindgren, *Proc. Cal. Acad. Sci.*, III (1890), 51; L. V. Pirsson, *Jour. Geol.*, IV (1896), 686, and *U.S.G.S., Bull. 237* (1905), 154; W. Cross, *Jour. Geol.*, V (1897), 684; J. W. Evans, *Q.J.G.S.*, LVII (1901), 38; G. W. Card, *Rec. G.S.N.S.W.*, VII (1902), 100; A. Lacroix, *Mater. Min. Mad.*, I (1902), 197.

It may be mentioned that the occurrence of primary analcite in monchiquites and analcite basalts and other such rocks has a bearing decidedly adverse to Brun's hypothesis that lavas are water-free, as does also the fact, well known to all petrographers, that many unquestionably fresh and recent pitchstones and other glassy rocks carry up to 10 per cent of H_2O.

With my three analyses are given others of closely similar rocks, which likewise contain small, rounded crystals of a mineral which looks like leucite and which in all cases is entirely isotropic and without twinning. Indeed, those from Colorado and Ireland were considered to be leucite basalts until chemical analysis showed the true character of the isotropic minerals. These two carry no biotite. In the case of the Bohemian rock, which, like those of Binzale Prunu, contains large plates of biotite, Hibsch apparently overlooked the significance of the dominance of soda over potash. This has been pointed out by Prior in the paper cited. Chemically, they are much like the Sardinian lavas, but are higher in CaO and also in TiO_2. The last two are also much lower in soda.

Classification.—The norms of the three Sardinian basalts analyzed by me are given in Table III. From this it appears that the Scano rock (A) falls in the subrang represented by the symbol III. (5) 6. 2. 5, there being just sufficient normative nephelite present to be taken into consideration. This subrang is as yet only represented by the Scano rock and a basalt glass from the Val di Noto, Sicily,[1] and the name of *scanose* has been given to it by me.[2] The Columbargiu rock falls in the subrang ornose, with the symbol III. 5. (2) 3. (4) 5. The Bonorva rock has the symbol III. 6. 1 (2). 4. This subrang, III. 6. 1. 4, has been called pienarose by Brouwer,[3] but a recalculation of his analysis shows that the pienarite (aegirite phonolite) described by him is really in III. 5. 1. 4. The name pienarose should therefore be applied to this subrang (III. 5. 1. 4), and the name pilandose may be given to III. 6. 1. 4, in which falls a Pilandsberg lujavrite described by him.[4]

TABLE III

NORMS OF ANALCITE BASALTS OF SARDINIA

	A	B	C
Or	4.45	4.45	15.59
Ab	28.30	31.44	15.98
An	10.56	11.95	3.61
Ne	6.53	....	14.62
Di	17.93	15.12	23.79
Hy	....	5.00	....
Ol	12.18	7.84	10.21
Mt	2.32	....	4.87
Il	9.73	9.45	7.60
Hm	1.76	7.23	....
Pf	....	2.18	....
Ap	2.69	2.35	2.02

Mode.—Owing to the very fine grain, the confused fabric, and the presence of abundant glass, it is impracticable to determine the mode by Rosiwal's method, and calculation of the mode by readjustment of the norms is also subject to some uncertainty through the presence of analcite. An attempt has, however, been made to determine the modes by comparison of the several norms with the respective thin sections, and checked by a Rosiwal measurement of the analcite areas. The results are given in Table IV, but they are to be regarded as only rough approximations.

[1] G. Pontes, *Atti Ac. Gioen.* (5), III, No. X (1910), 7.

[2] H. S. Washington, *C.R. XII Cong. G. Int.*, 1913.

[3] H. A. Brouwer, *Transv. Nefel. syen.* (1910), 50.

[4] *Ibid.*, p. 132. This course has been decided on in conference with Drs. Cross and Iddings.

These three are all similar in their general features. In C, it is evident that some of the normative olivine has gone into the biotite. It may be added that the small amount of excess TiO_2 (represented normatively as perofskite) has been assigned to biotite, the somewhat abnormal composition of which is indicated by its optical characters. The large amount of glass is very striking, as well as the general composition which must have been assigned to it in each case had it crystallized. For A and B, it would have about the composition Ab_1An_1, including a little orthoclase with a small amount of analcite. In C, the 40 per cent would be distributed approximately as follows: orthoclase, 15; andesine (Ab_2An_1), 20; analcite, 5. While the figures given here and in the table are admittedly only rough approximations, yet there can be no doubt that they give an idea of the general order of the various minerals present.

TABLE IV

	A	B	C
Analcite	8	5	10
Augite	20	20	25
Olivine	12	6	10
Biotite	....	5	....
Ores	15	18	13
Apatite	3	2	2
Glass	42	44	40

A. Mode of analcite basalt. Scano.
B. Mode of biotite-analcite basalt. Monte Columbargiu.
C. Mode of analcite basalt. Bonorva.

Rock name.—The name of analcite basalt, first proposed by Lindgren,[1] is entirely applicable to these rocks, and is preferable to that of monchiquite, which was originally applied to rocks in which the analcite is present in the base or as a glass of the same composition. It is worthy of remark that, had the rock solidified under such conditions as to be holocrystalline, the modes given above show that a very considerable amount of andesine or labradorite would have been present (as has been the case in the Bohemian rock cited above). In this case, the name analcite basanite would have been appropriate.

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[1] W. Lindgren, *Proc. Cal. Acad. Sci.*, III (1890), 51.

The presence of considerable biotite in the rocks of Binzale Prunu and Ghizo is so striking that they may be considered to form a special type of analcite basalt, which may be called ghizite, if a special name be deemed advisable.

The occurrence of analcite in these rocks, as well as in those of Colorado, Ireland, and elsewhere, which, without chemical analysis, can only with great difficulty be distinguished from leucite, so that the rocks are on superficial examination considered to be leucite-bearing, indicates the necessity of chemical analysis, and the advisability of a revision of some of the occurrences of so-called leucitic rocks. This is especially true of certain regions, such as Bohemia, Kula,[1] and Trebizond, where basalts containing a mineral supposed to be leucite occur, but where the rocks and the regional magmas are eminently sodic rather than potassic. As a general rule, as is well known, analcite is apt to occur in the rock base as the last, or one of the last, products of crystallization, but its undoubted occurrence in the instance described in this paper and those occurrences cited in the table of analyses show that its presence in leucite-like phenocrysts may be much more general than has been hitherto supposed, and may clear up some of the obscurities surrounding the occurrence of leucite.[2]

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[1] It now seems highly probable, in view of the present study, that the supposed leucites of the "leucite" kulaites of Kula are in reality analcites. Though the potash is higher than in the rocks cited above, yet they are dominantly sodic, and the supposed leucites rarely show optical anomalies.

[2] Cf. H. S. Washington, *Jour. Geol.*, XV (1907), 277.